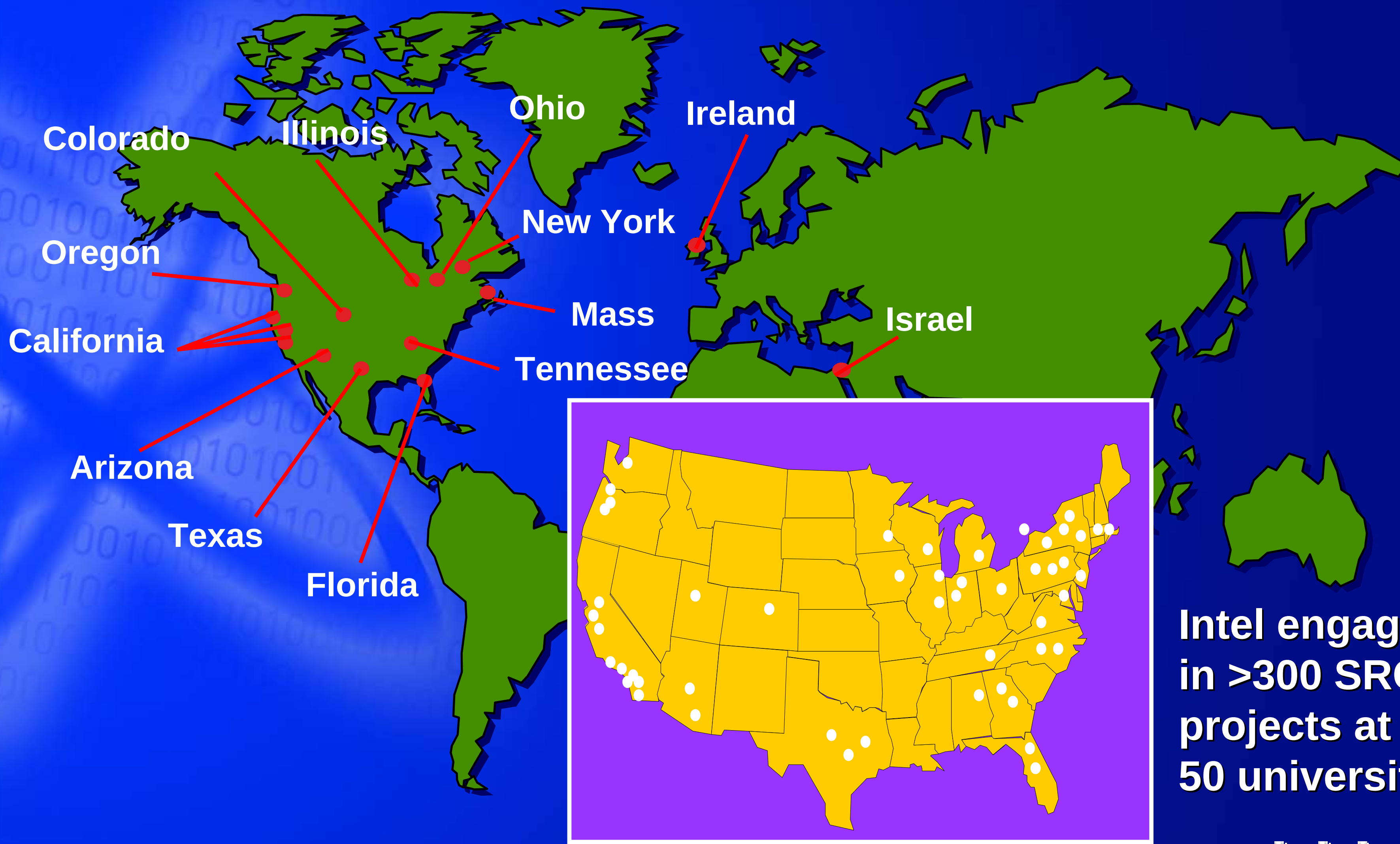
Nano-Scale Technology: Getting from Science to Engineering

David Tennenhouse

Vice President, Corporate Technology Group, Intel Corporation

Intel University Research

Intel-supported Nanotechnology Research at Universities



Intel engaged in >300 SRC* projects at 50 universities

*Semiconductor Research Corp

Intel Capital Investments

Nanotechnology

nanosys™

Sensor Networking

Crossbow® Technology Inc.

MEMS

IRIDIGM™

Biotech

Surface Logix

* Other names and brands may be claimed as the property of others.

Where does new technology come from?

Universities are the "packet switches" of new ideas

Is the U.S. investing enough in University Research to take advantage of nanotech?

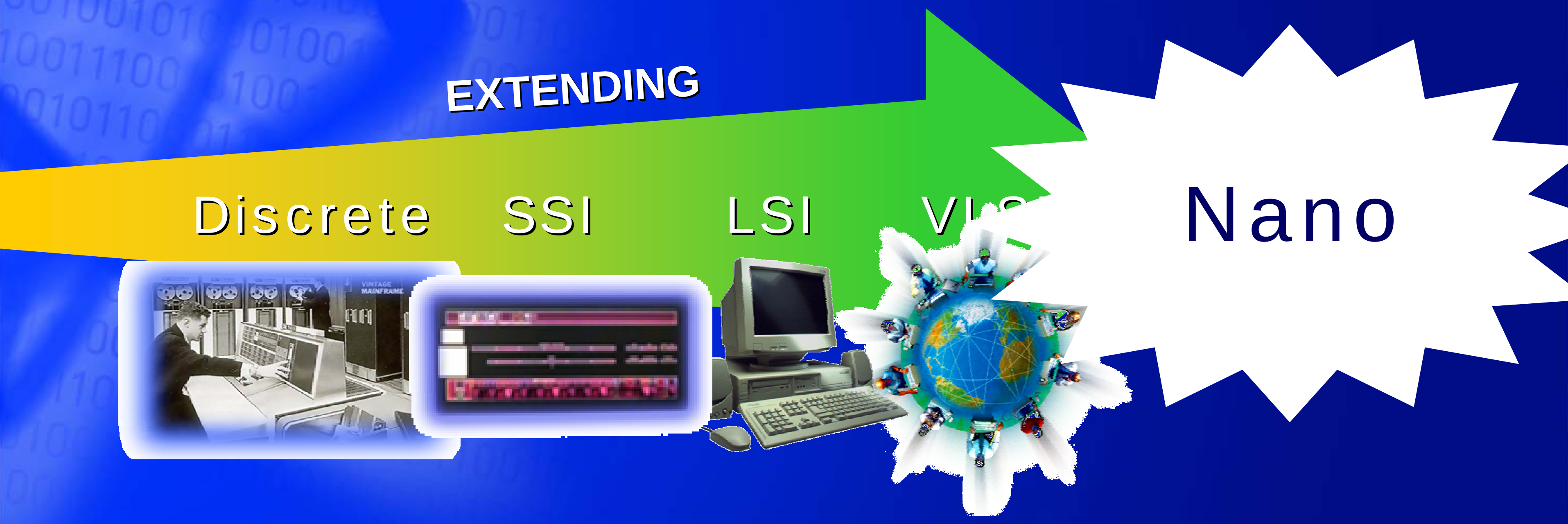
The Research Gap

- **Basic Research on Nanotech (NNI) is creating dramatic opportunities to improve productivity & quality of life.**

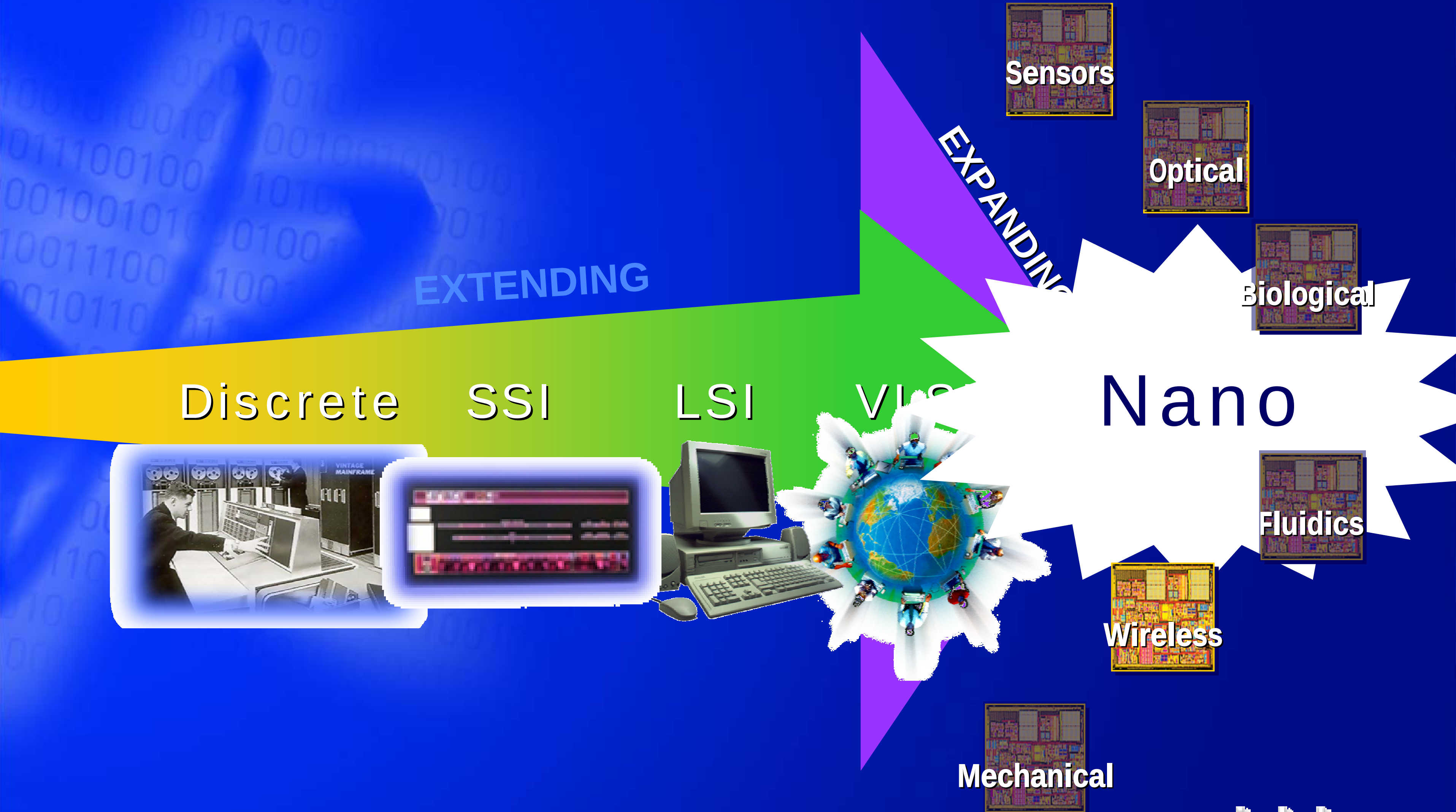
- **However …**
  University Applied Research is under-funded
  - **Key Example: Computer systems & network research**
  - **Historic source of today's productivity gains**
  - **In general, U.S. government spending on university engineering research has not kept up with its importance to the economy / share of GDP!**

→ Time for a thoughtful review of EE/CS funding

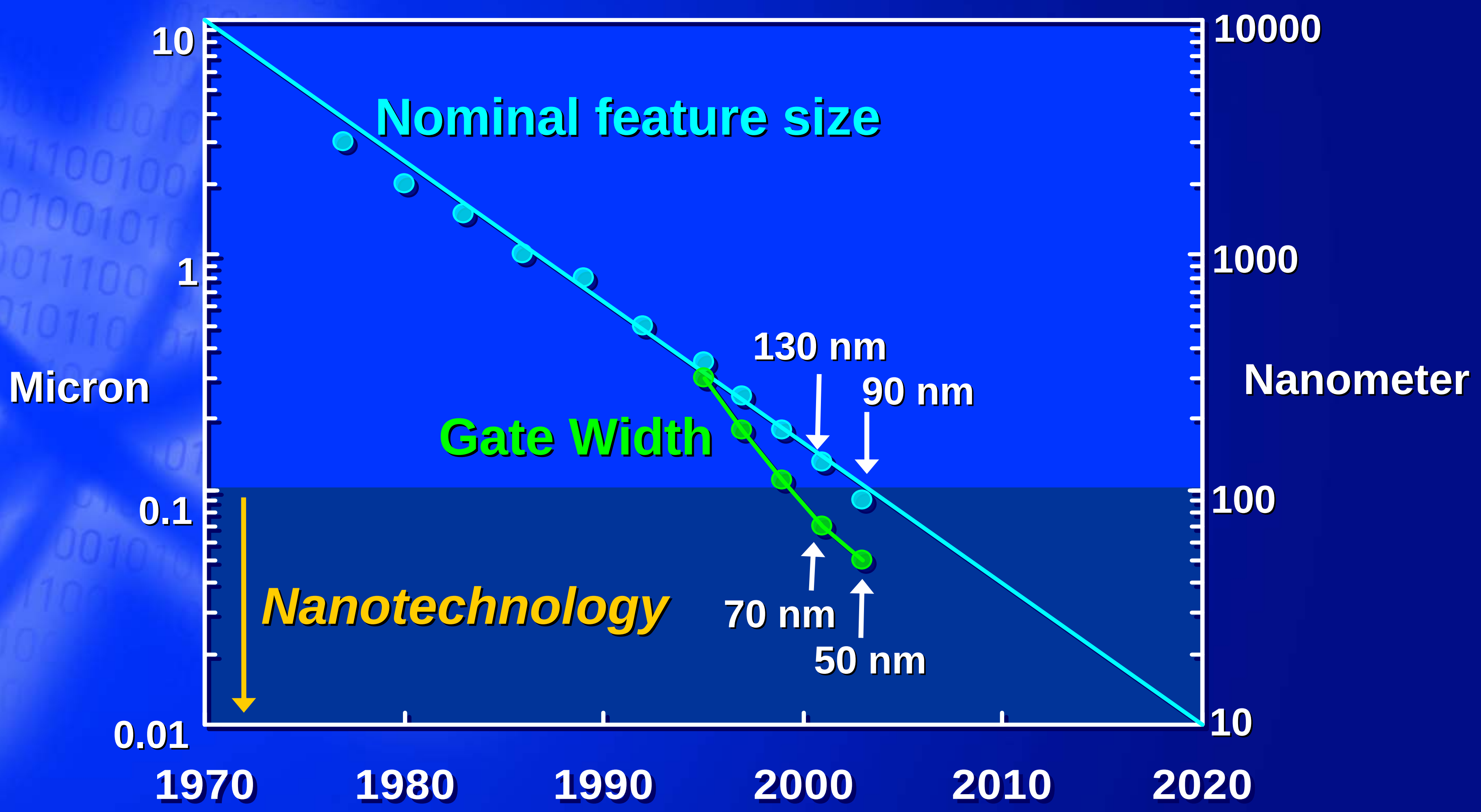
Extending Moore's Law



Expanding Moore's Law



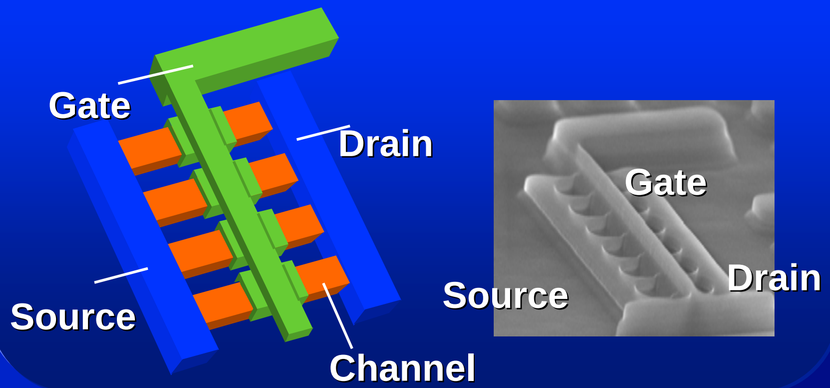
Silicon Nanotechnology is Here!



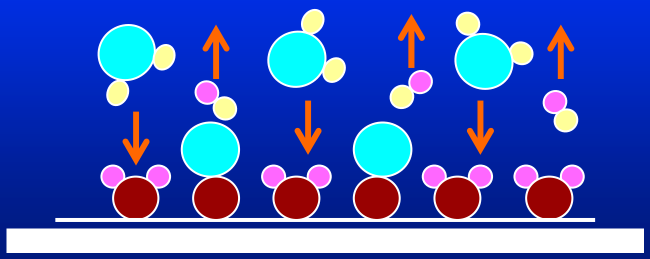
Continued CMOS Scaling: 65 nm ⇨ 22 nm

Drawing Smaller Rectangles: EUV

New Transistor Structures



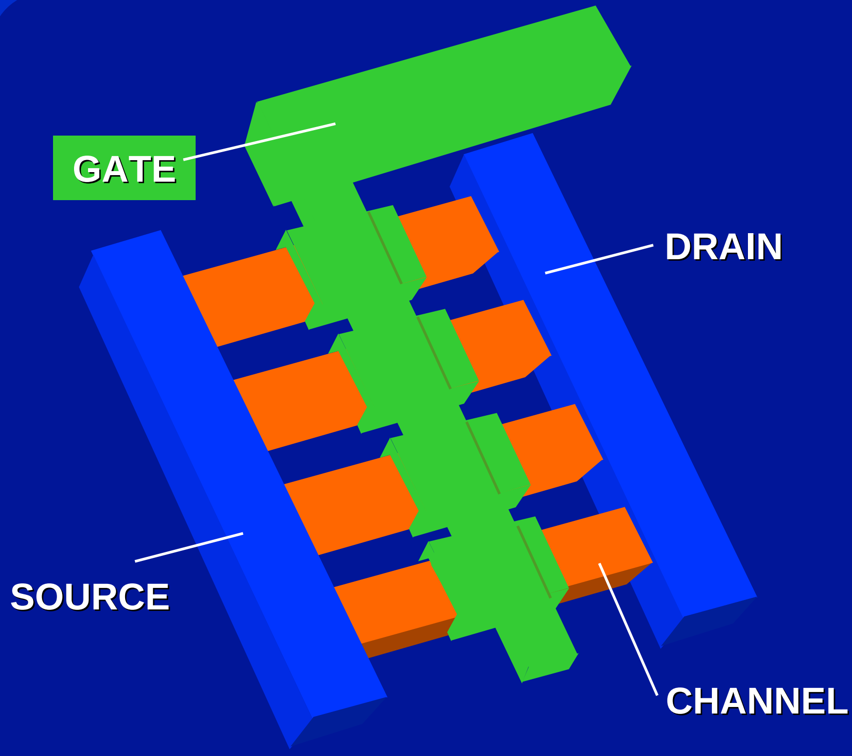
Thinner Rectangles: Bulk Self-Assembly

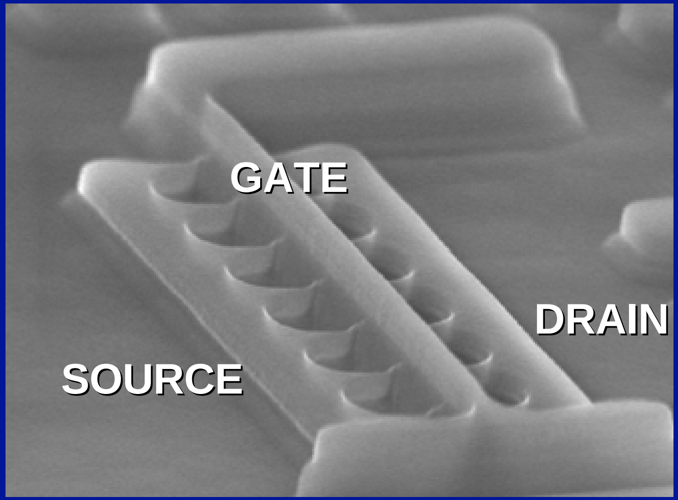


Performance Scaling an Issue

- Very small # of dopants
- Device and interconnect speed
- "Stretch" performance with:
  - Cooling and / or 3D stacking?
  - "Bulk" nano-materials?

Tri-Gate Transistor





Source: Intel

Technical details presented at:

ISSDM Conference, Japan, Sept 17, 2002

Continued CMOS Scaling: 65 nm ⇨ 22 nm

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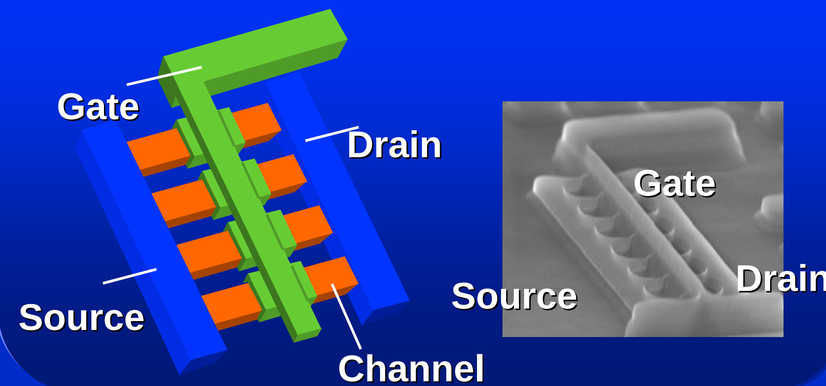
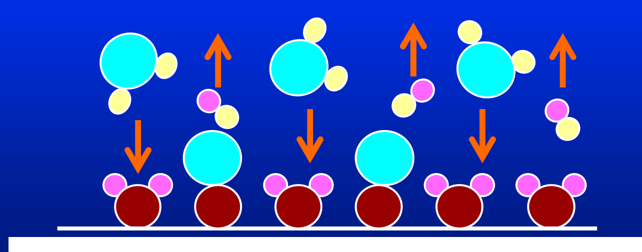
New Transistor Structures



Thinner Rectangles: Bulk Self-Assembly



Performance Scaling an Issue

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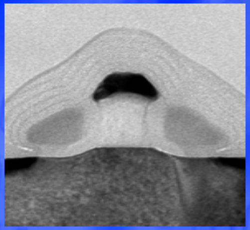
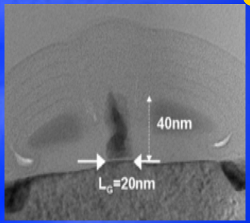
----2003

65 nm Node
2005



30 nm Prototype
(IEDM2000)

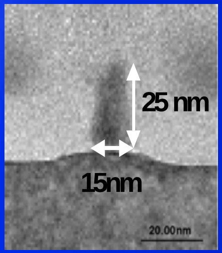
45 nm Node
2007



20 nm Prototype
(VLSI2001)

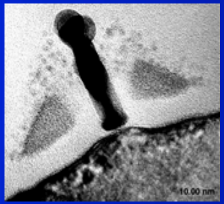
–2011 —

32 nm Node
2009



15 nm Prototype
(IEDM2001)

22 nm Node
2011



10 nm Prototype
(DRC 2003)

–2013 — 2019

16 nm
2013

11 nm
2015

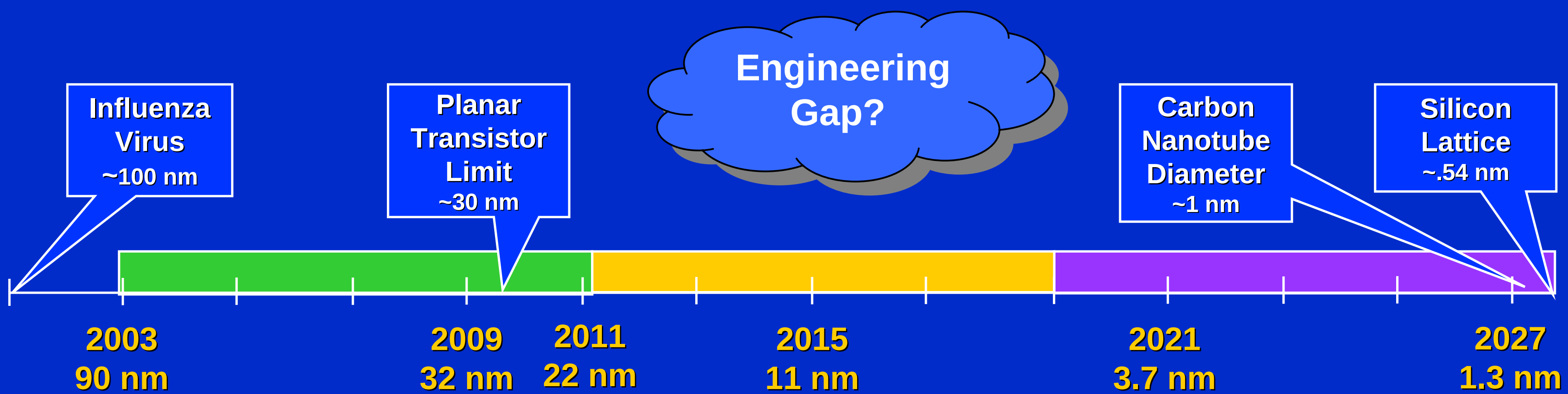
8 nm
2017

2019

Source: Intel; Morales and Lieber Science, 279, 208, 1998

Silicon Nanotechnology Evolution

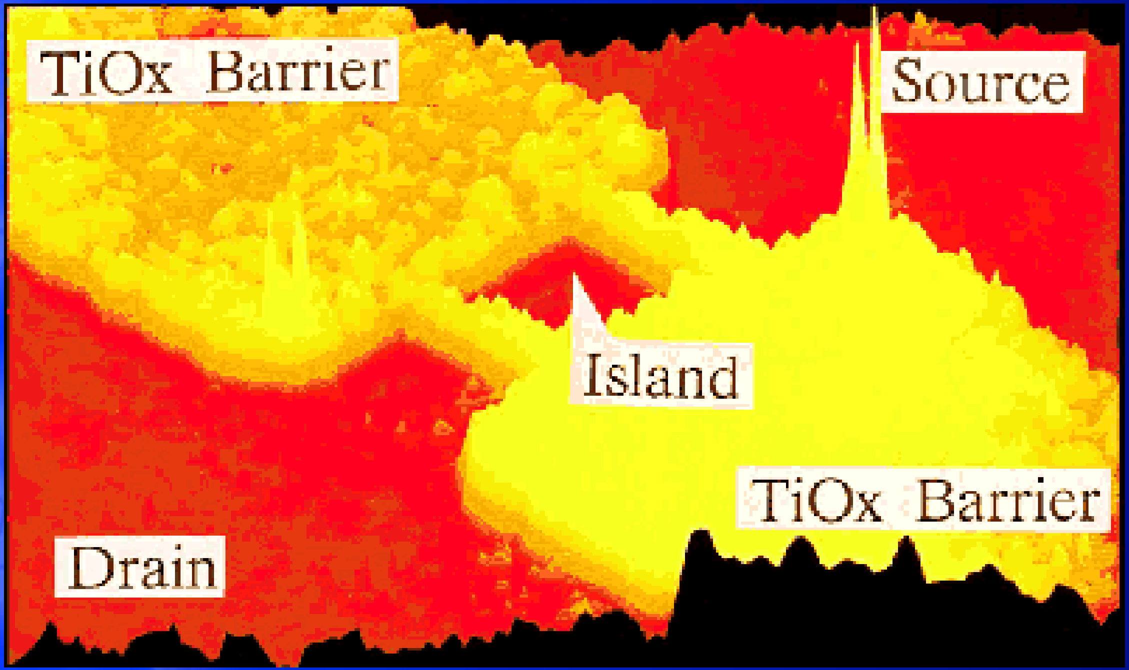
- Continued CMOS Nanoscaling
- Non-classical CMOS / Charge-based devices
- Transition to Novel Devices



Non-Classical Charge-Based Devices
What are we looking for?

- Required Characteristics:
  - Gain / Drive Current
  - Energy Efficiency / Speed
  - Scalability (multiple generations)
  - Room Temperature Operation
  - Operational Reliability
- Preferred Approach:
  - Silicon Process and Architectural Compatibility

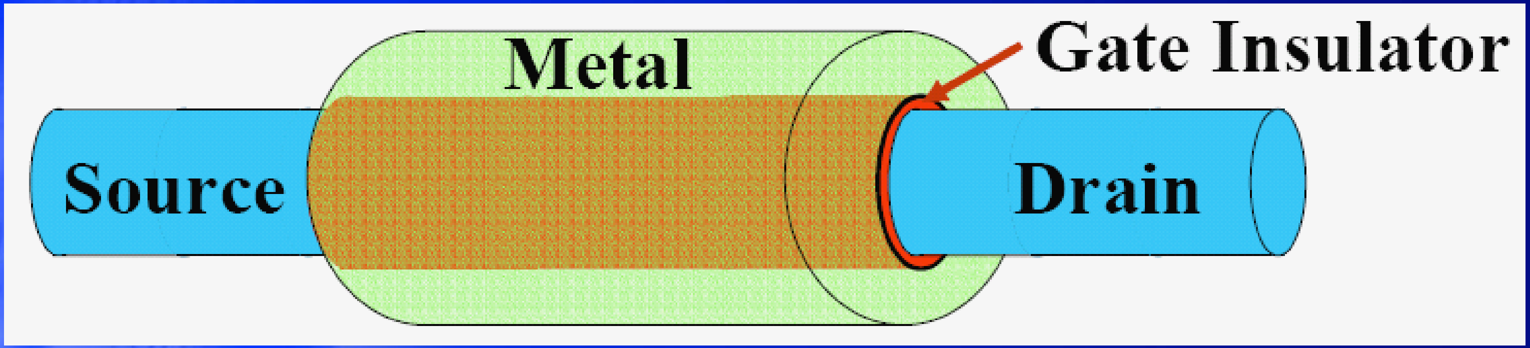
Example: Room Temperature Single Electron Transistor (SET)



Courtesy, NEC, IEDM 2000, PP 481

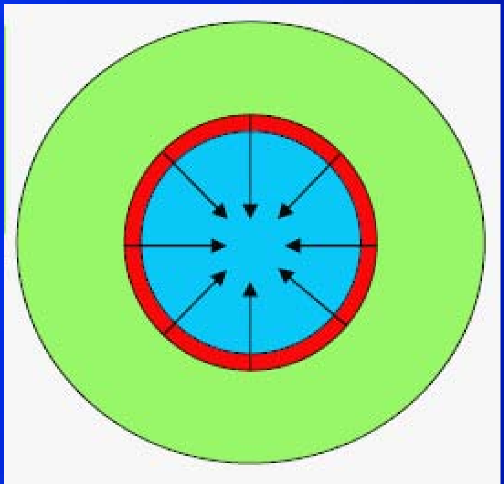
- **Single electron in "island" controls current flow from source to drain**

Closing in on the Ideal MOS Transistor



Fully Surrounding Metal Electrode

High Mobility Channel



High-K Gate Insulator

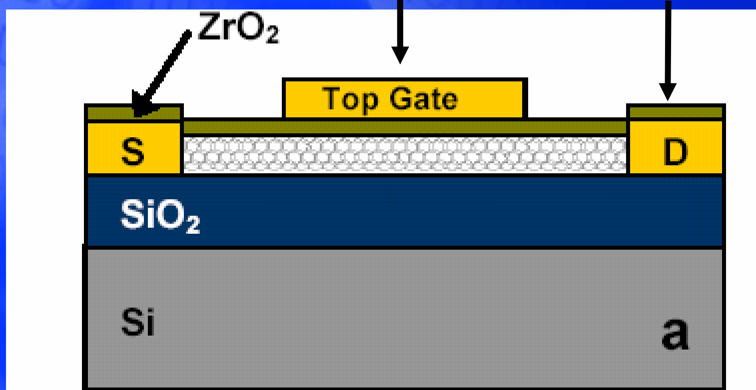
Low Resistance Source / Drain

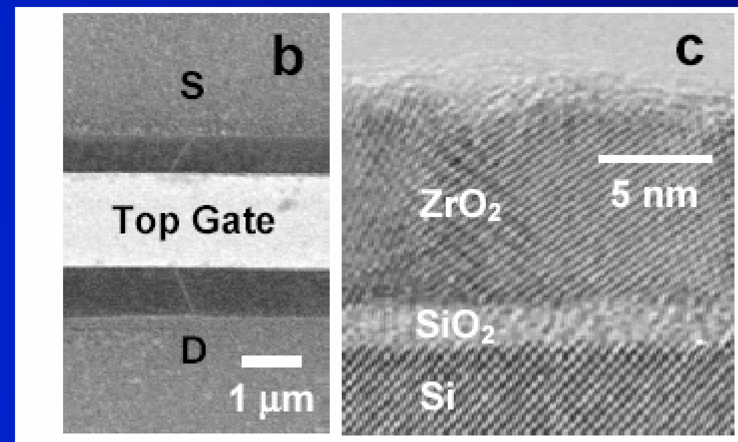
Band Engineered Semiconductor

Example: Nanotubes

E-beam Ti/Au gate

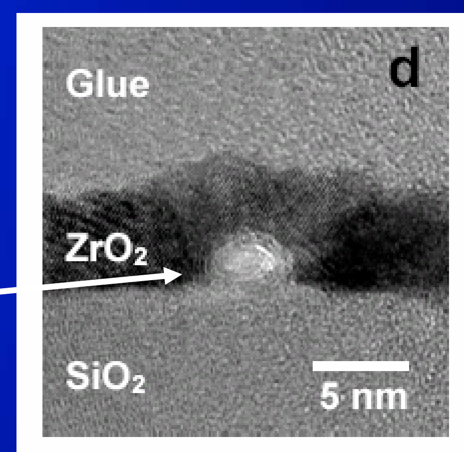
Mo S/D





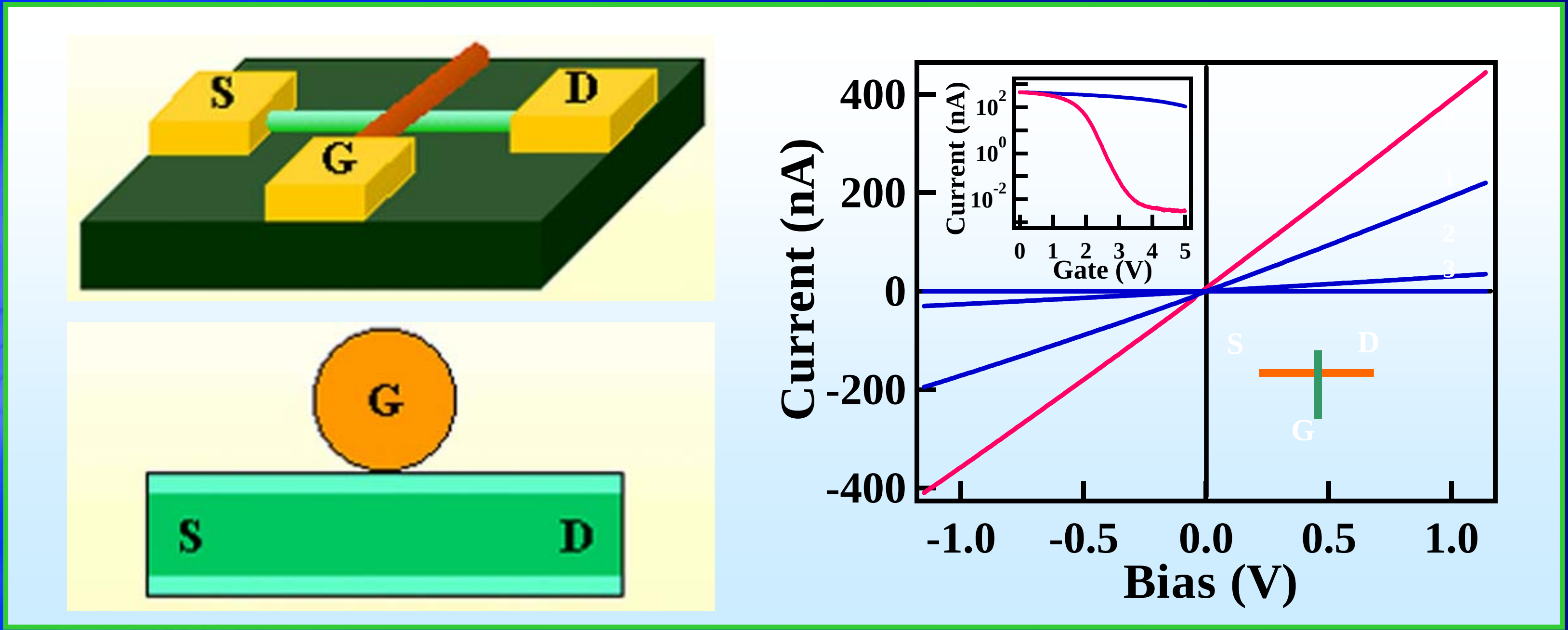
8 nm ZrO2

1.4 nm diameter single wall CNT



McEuen et. al, . Cornell University

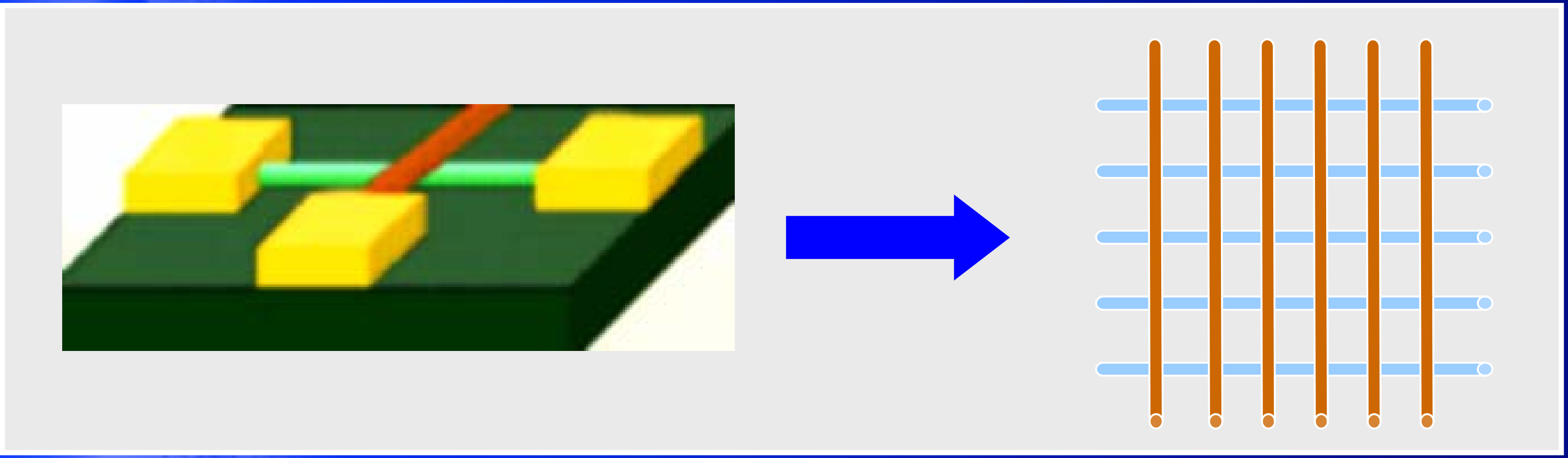
Example: Crossed Nanowire FETs



- In crossed nanowire FETs (cNW-FET), all critical nano-scale metrics are defined by synthesis and assembly:
  - **Channel width by the active nanowire diameter (to 2 nm)**
  - **Channel length by the gate nanowire diameter (to 1-2 nm)**
  - **Gate dielectric oxide coating on the nanowires (to 1 atomic layer)**

Huang, Duan, Lieber et al., *Science* **294**, 1313 (2001)

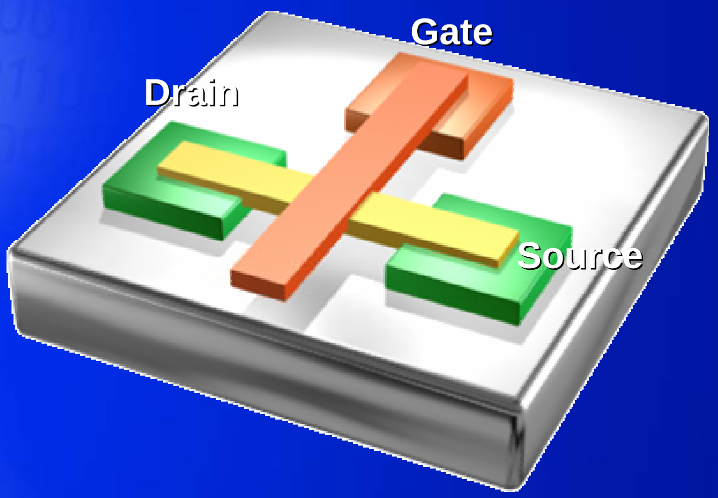
Scaling: Crossed Nanowire Arrays



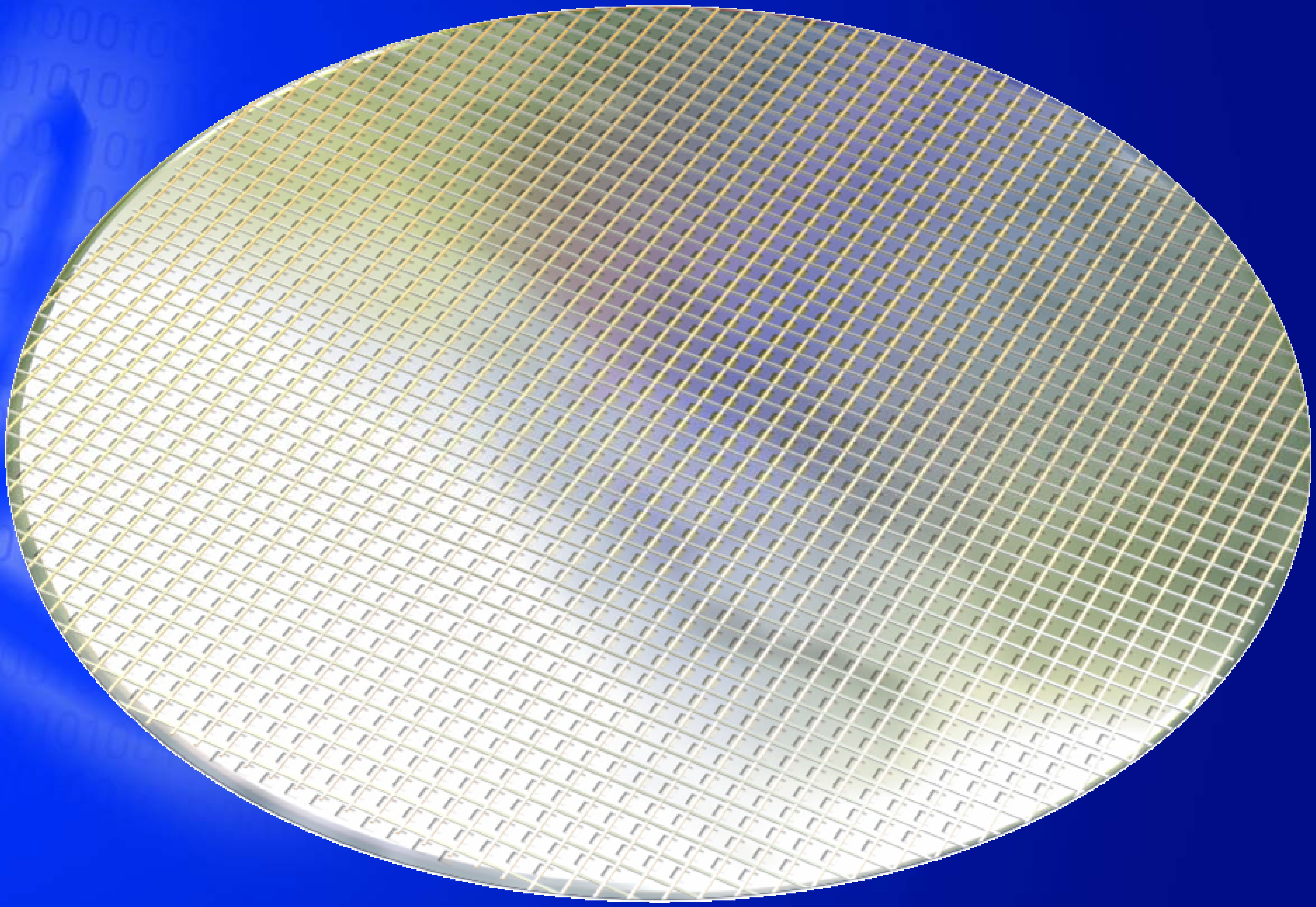
- Nanowires serve dual purpose
  - Active devices and interconnects

➢ Scaling and potential for top-down / bottom-up integration

C. Leiber et. al. , Harvard



Artist's Conception



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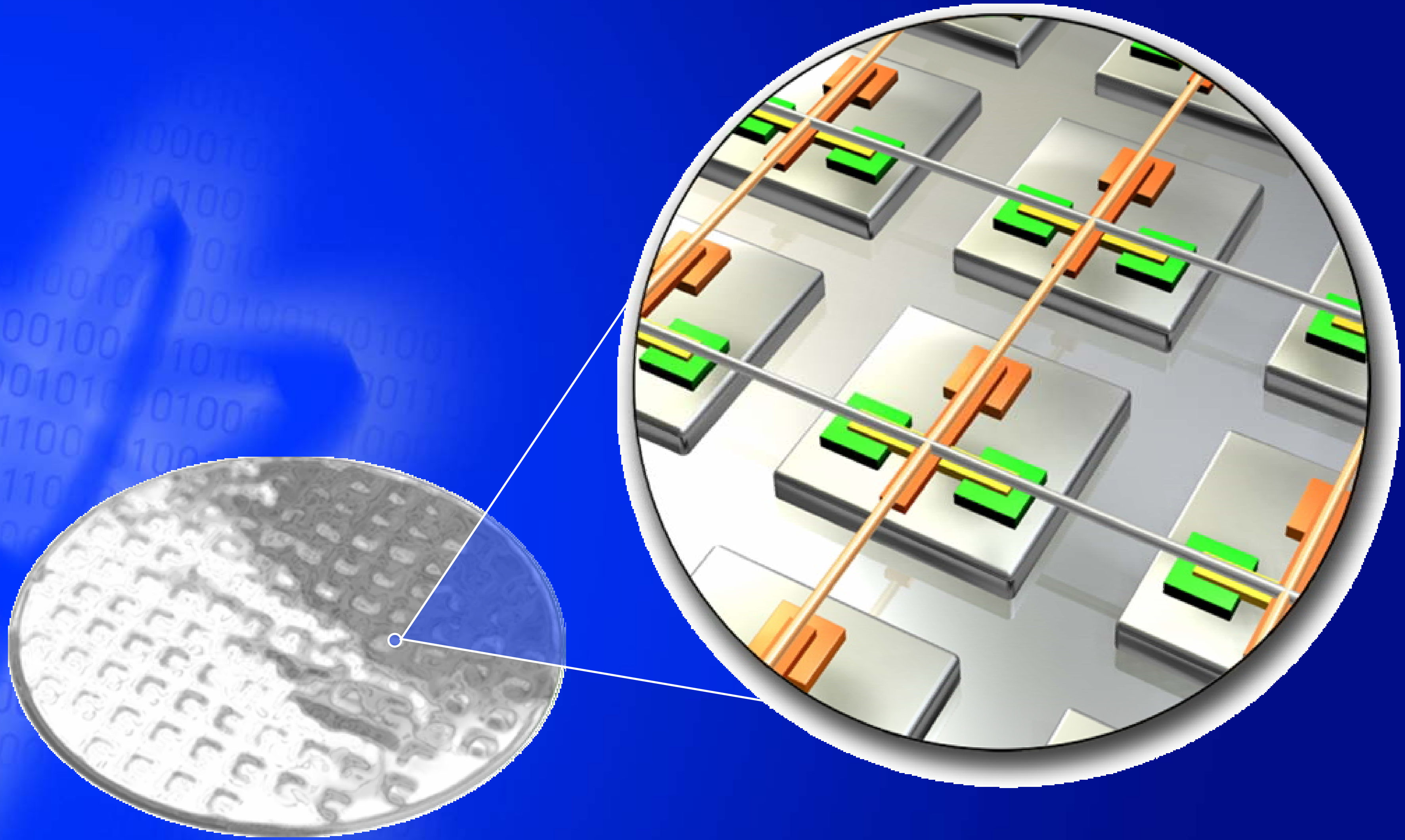

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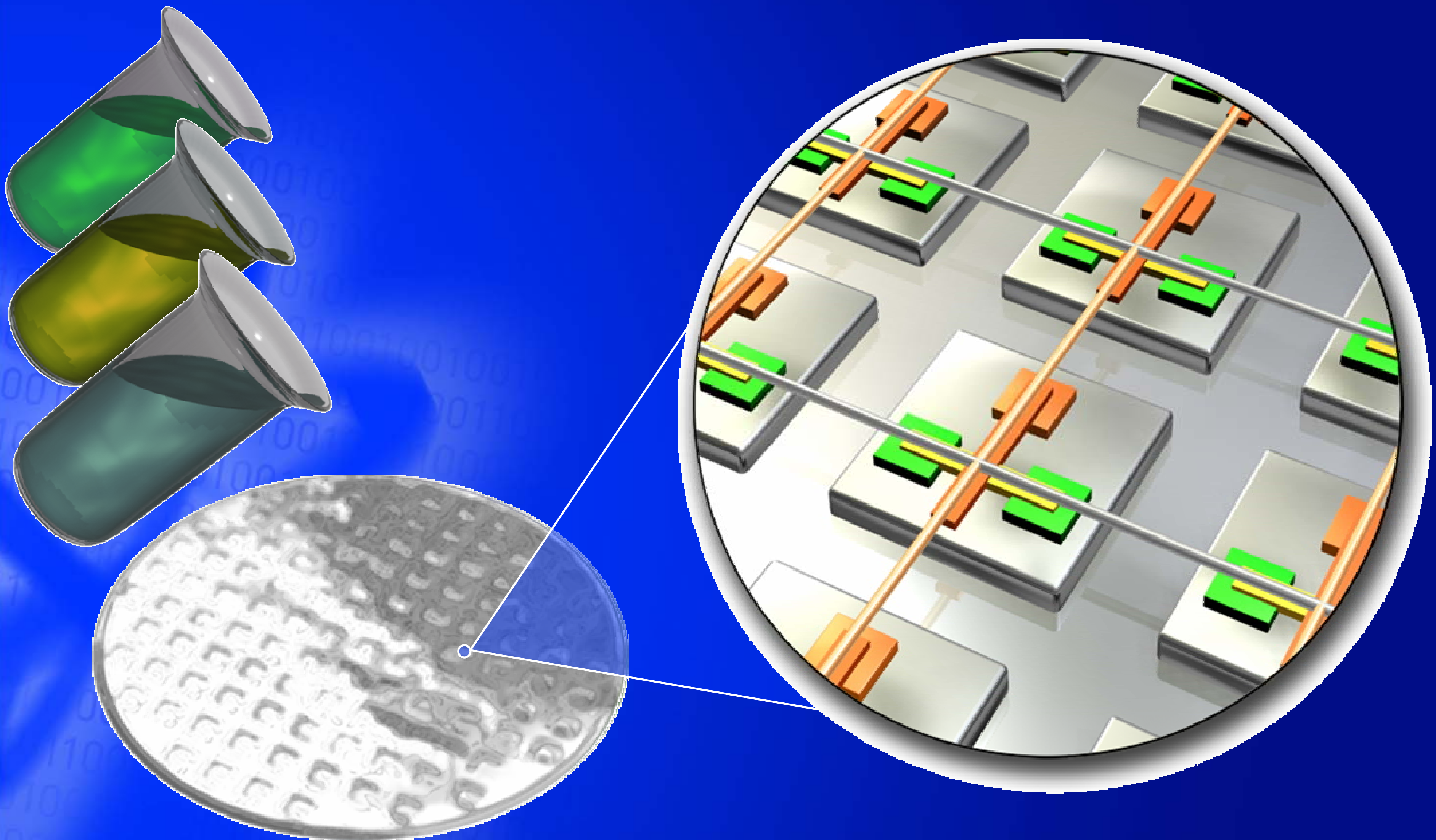
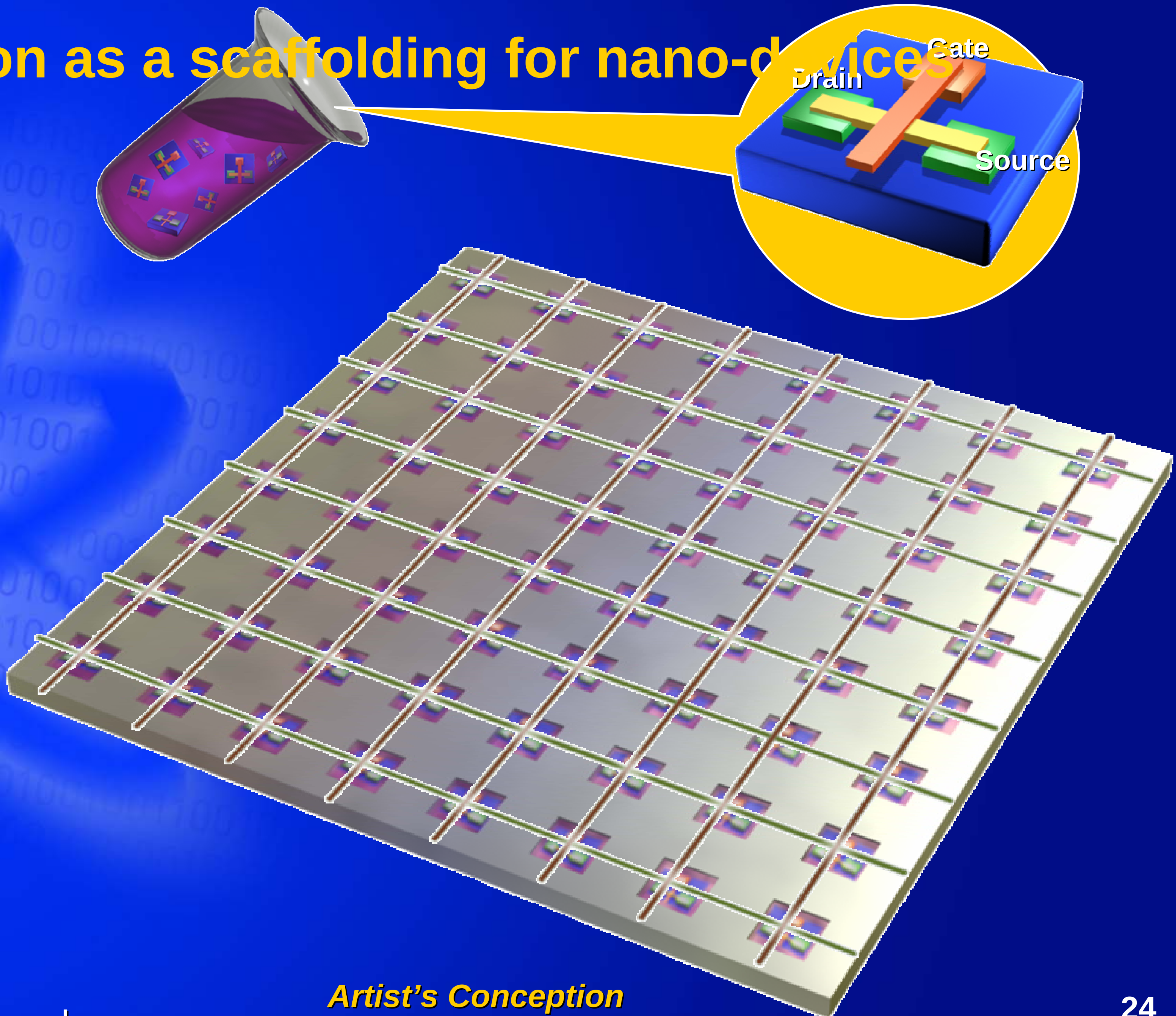


Artist's Conception

Silicon as a scaffolding for nano-devices



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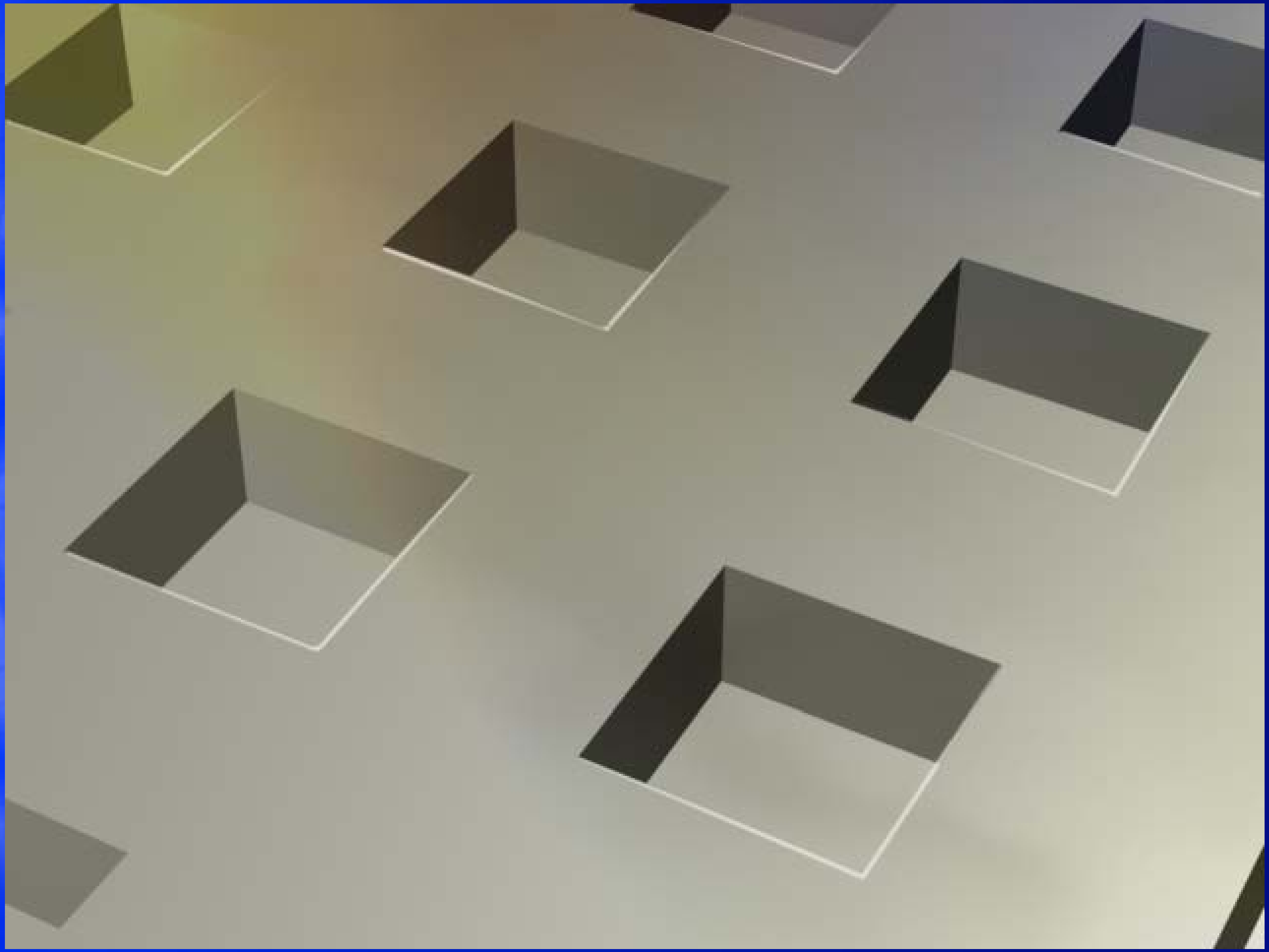

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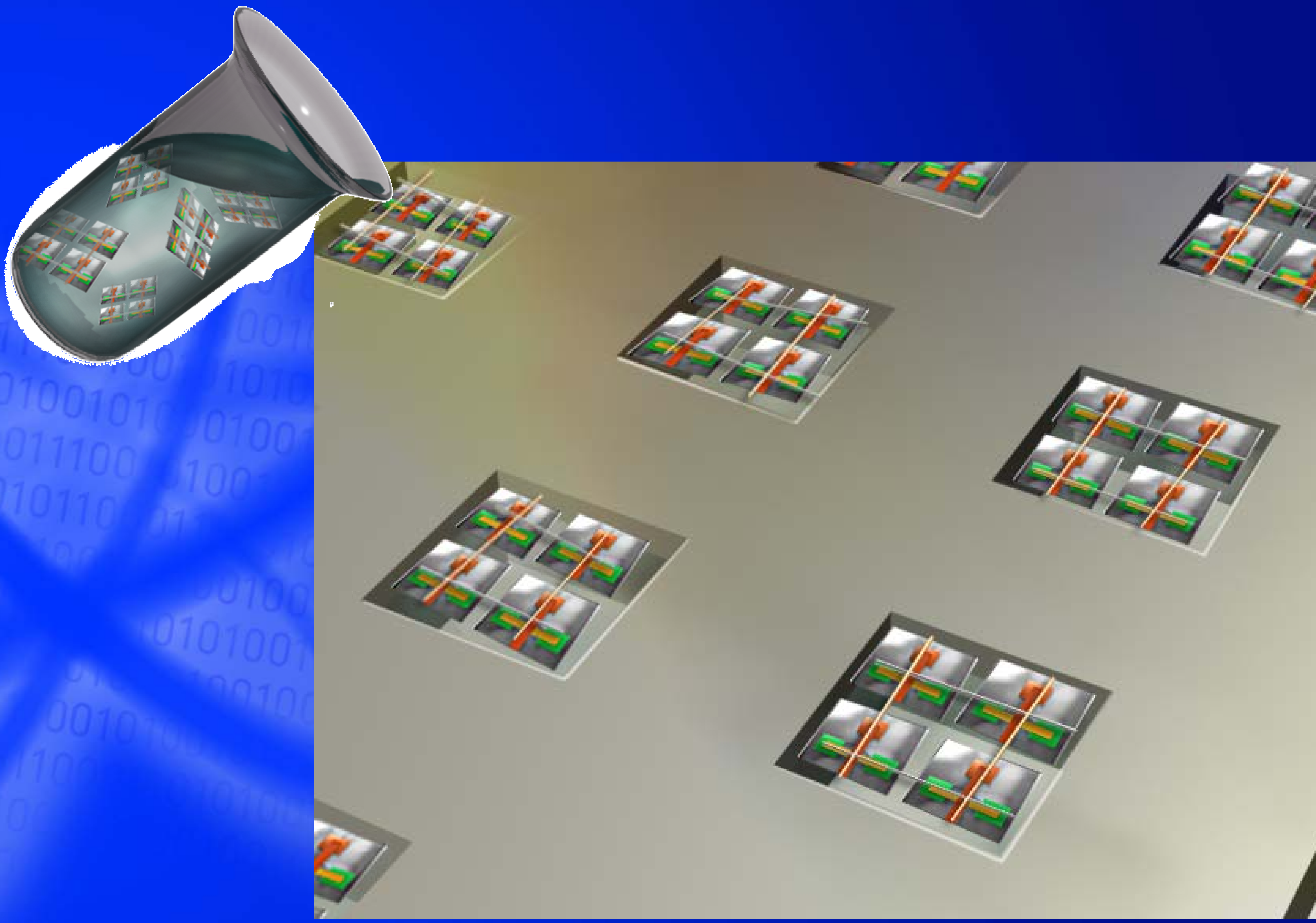


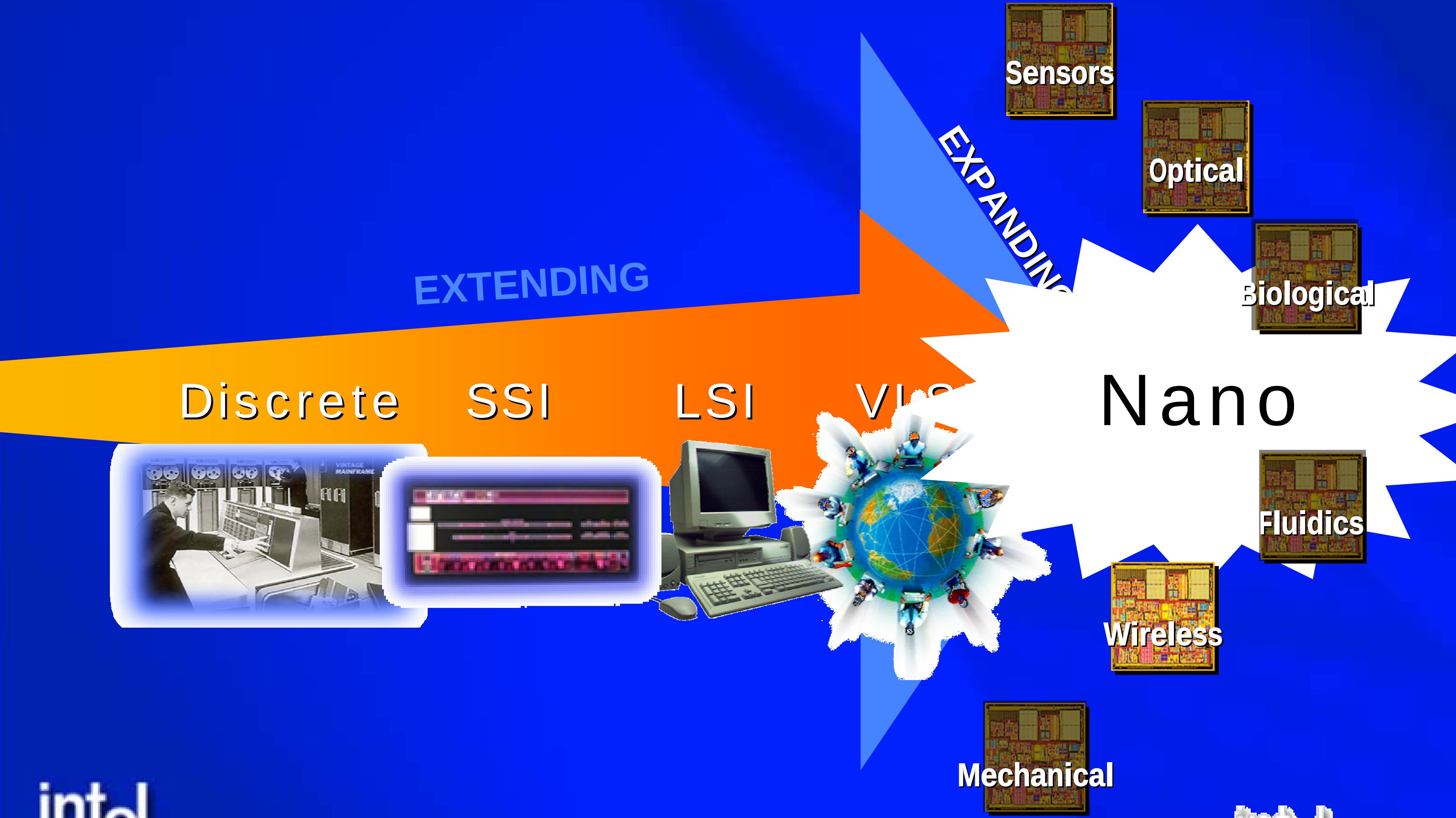
Artist's Conception

Call to Action

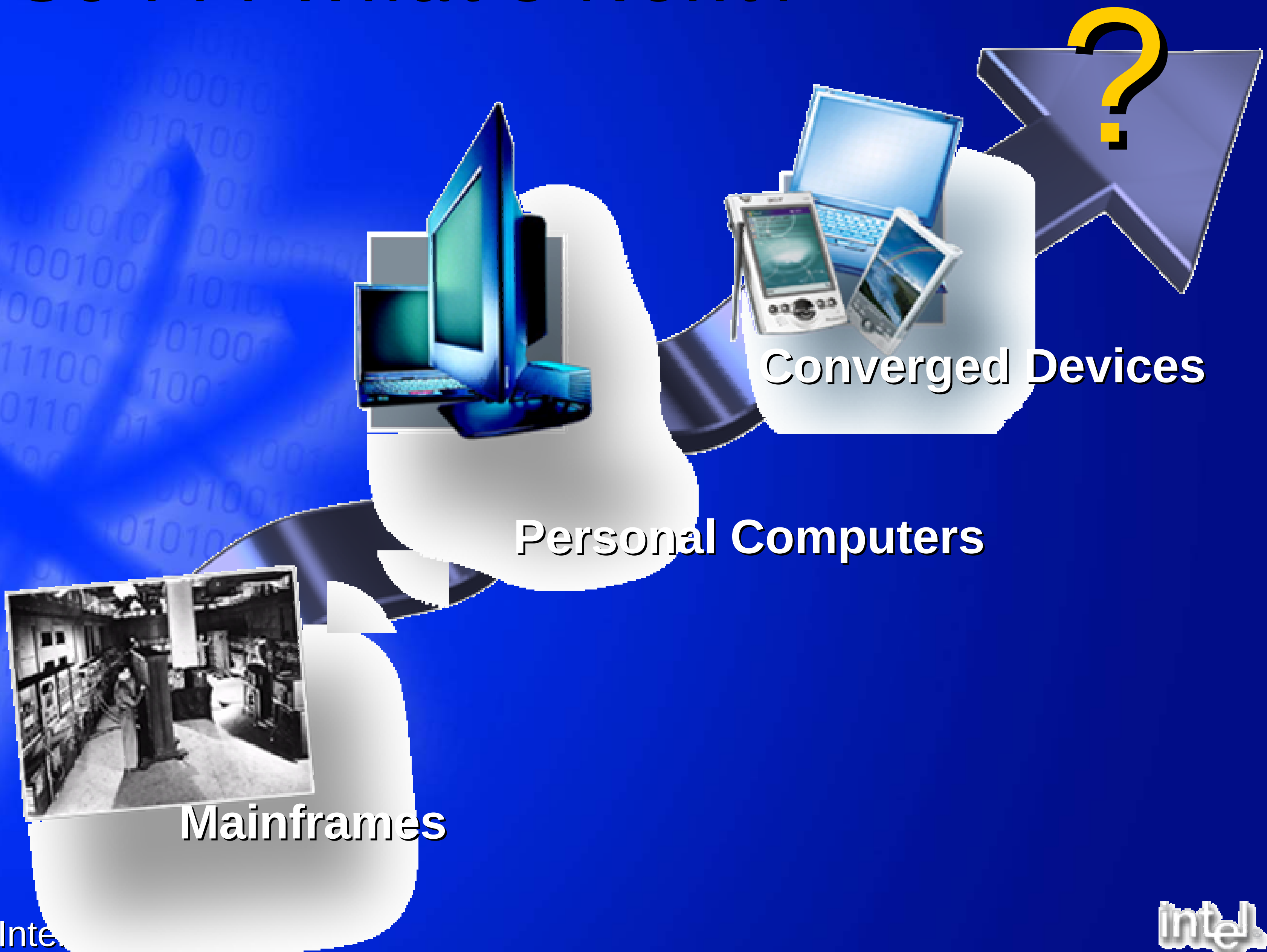
Its time to focus on non-classical charge-based devices

- Gain consensus on 2-4 best approaches and grow more options around them
- Industry / government partnership to support university engineering research
  - Bench-marking & Instrumentation
  - Manufacturing technologies
  - Using bottoms-up at "intercept" scales / geometries
  - …

Expanding Moore's Law



So . . . What's Next?



Proactive Computing

Proactive Computing

Today: Computers are interactive

- We are always waiting for them or vice-versa

Tomorrow: Computers will be Proactive

- They will anticipate our needs and act on our behalf

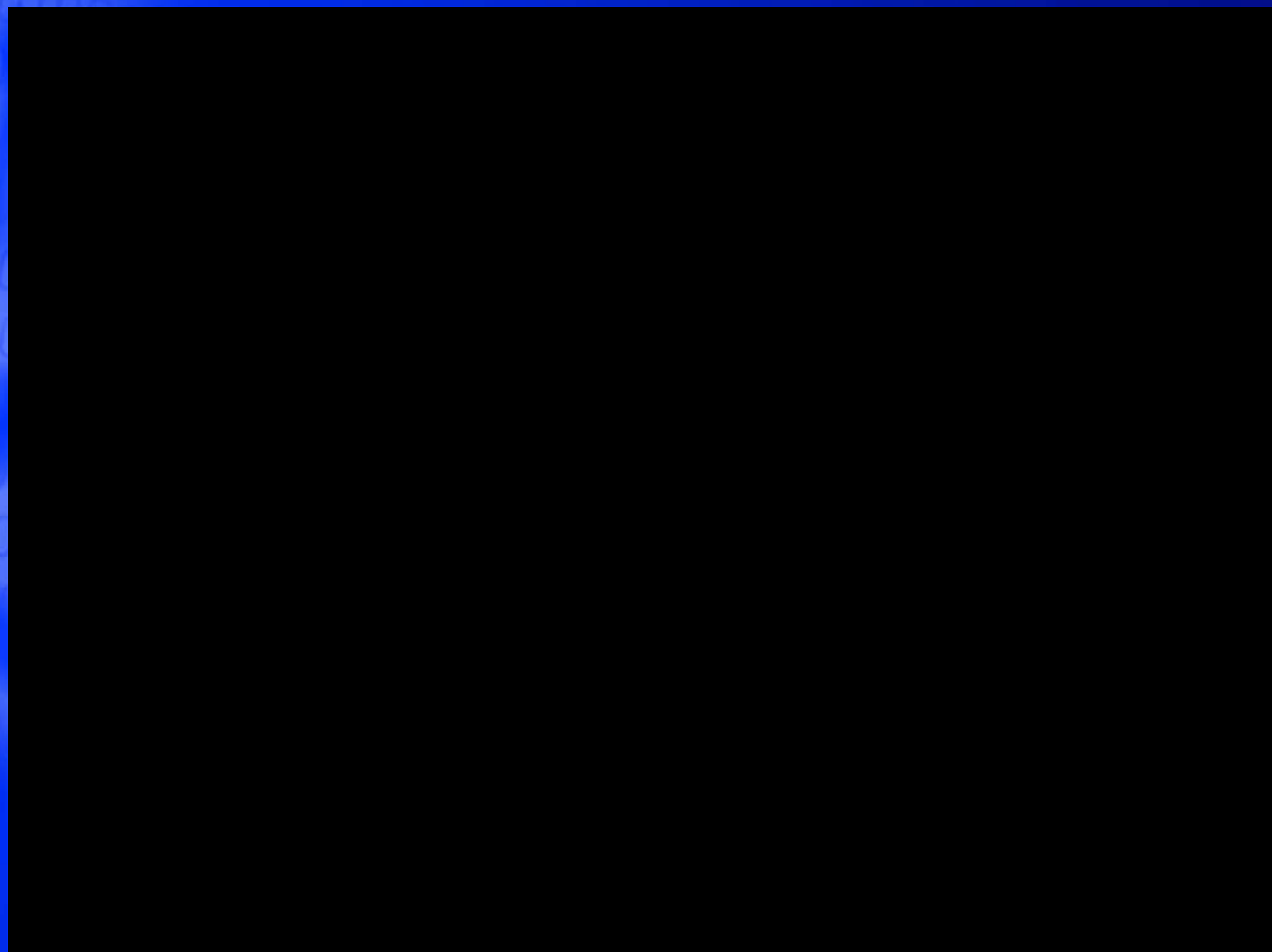
Proactive Health – Usage Studies

Mid-Stage Decline

Labscape

Condition Based Maintenance

Ad Hoc Networks



Enabling Transition

We are on the verge of:

- a vast increase
- in the spatial & temporal fidelity at which
- we instrument & analyze the physical world.

This will enable real-time proactive computing

- It is starting to happen now
- Nanotechnology will accelerate the process

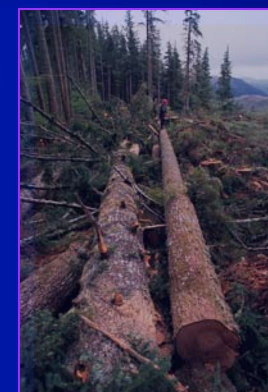
Bring "Deep IT" to Key Sectors of the Economy

Financial

IT

Health / Life Sciences / Agriculture

Government



Environmental

Transportation

Retail

Distribution

Manufacturing

Making Proactive Happen

Make it Personal	Empowering individuals and addressing their concerns over security and privacy
Closing the Loop	Bridging the gap between anticipating and acting on needs – predictably, and under human supervision
Anticipation	Creating proactive software that anticipates our needs and produces answers before they are required
Dealing with Uncertainty	Using statistical modeling to deal with uncertainty inherent in the physical world
Planetary Scale Systems	Developing software that works across a wide range of diverse platforms and networks
Deep Networking	Locally networking billions of embedded nodes; driving computing deeper into the infrastructure that surrounds us
Getting Physical	Connecting computers directly to the physical world around them

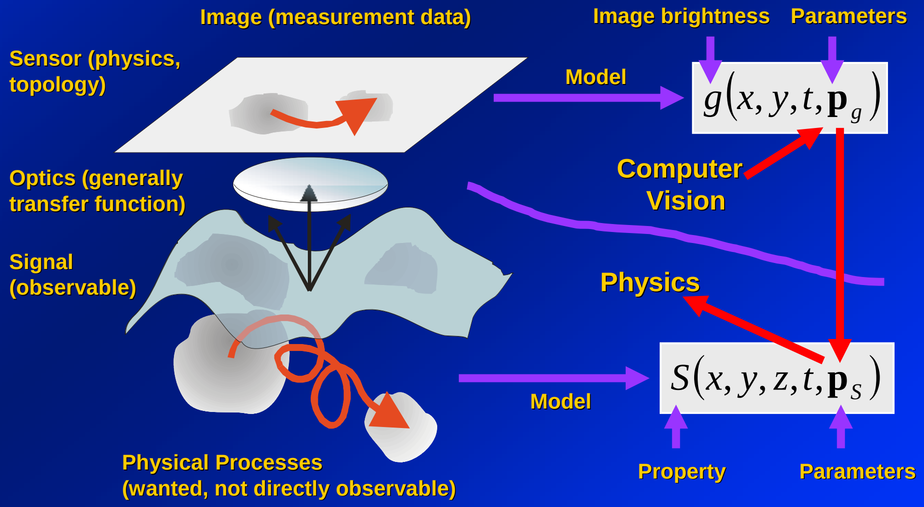
Nano-Scale Machine Vision

- Make it Personal
- Closing the Loop
- Anticipation
- Dealing with Uncertainty
- Planetary Scale Systems
- Deep Networking
- Getting Physical

Getting Physical

Connecting computers directly to the physical world around them

- **Goals: Image reconstruction, object recognition, & automation to improve accuracy & speed of development and debug process for Intel mfg**



Precision Biology

- Make it Personal
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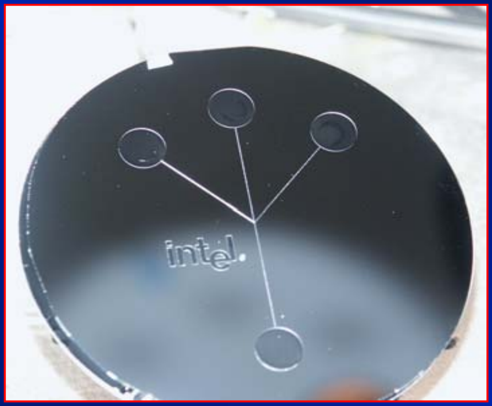
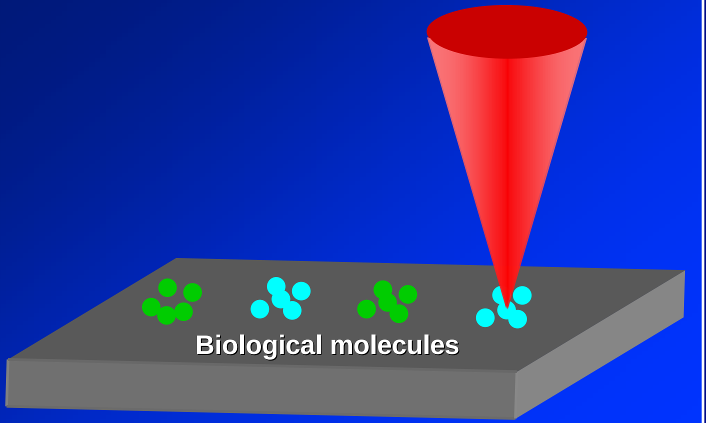
Getting Physical

Connecting computers directly to the physical world around them

- **Goal: Early disease detection. Create technology to perform single molecule detection and analysis of biomolecules, such as DNA**





Radio Free Intel

- Make it Personal
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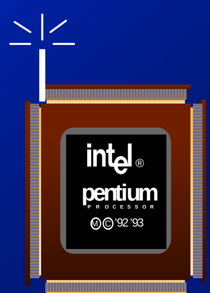
Deep Networking

Locally networking billions of embedded nodes; driving computing deeper into the infrastructure that surrounds us

- **Shift the analog / digital balance**
- **Get analog circuits onto *standard* CMOS processes**
- **Reconfigurable digital logic & software defined radio enhance performance with Moore's Law**

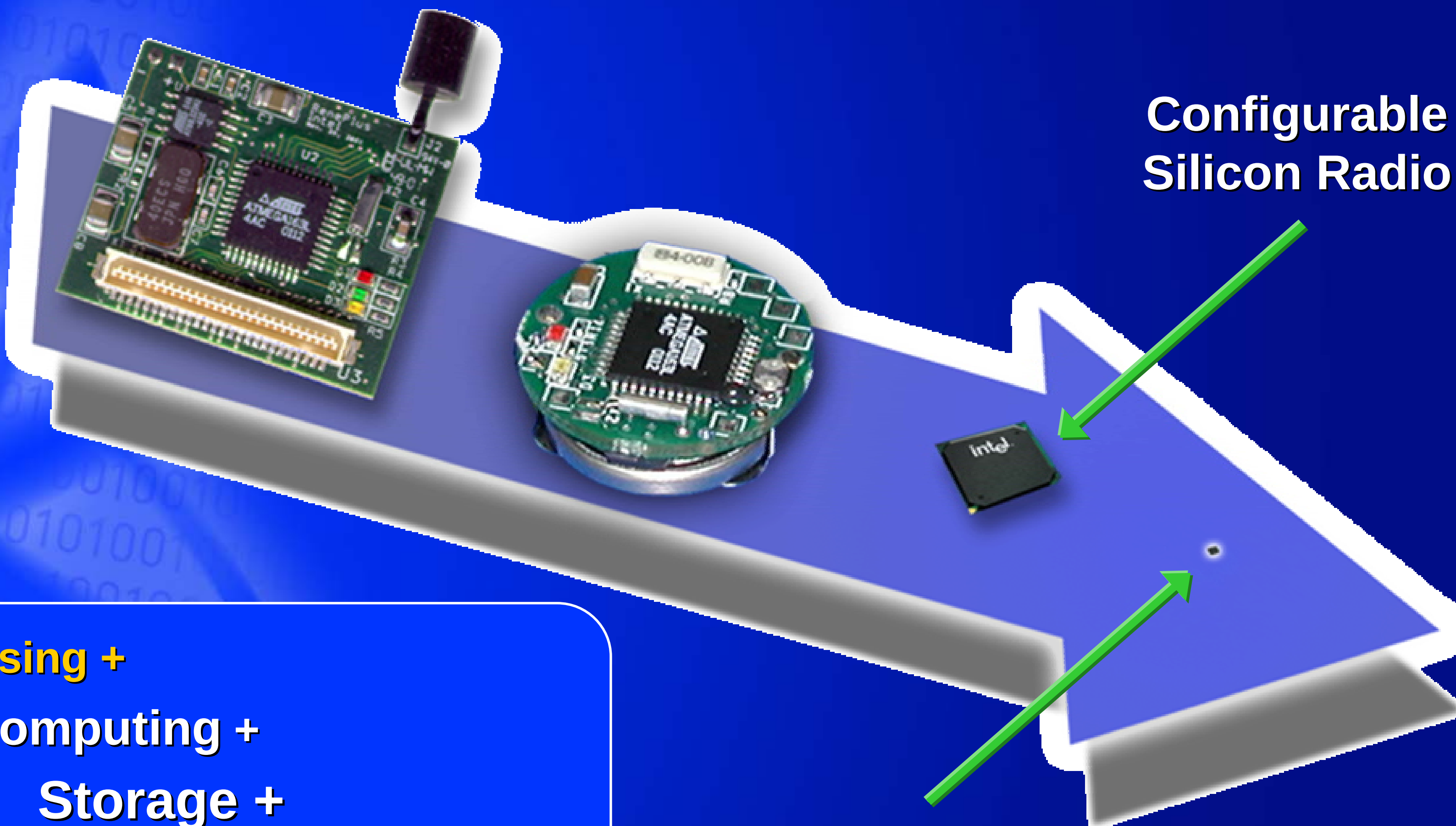
CMOS RF



RF MEMS

Ultra Wide Band: "Moore's Law Radio"

The road to smart dust....

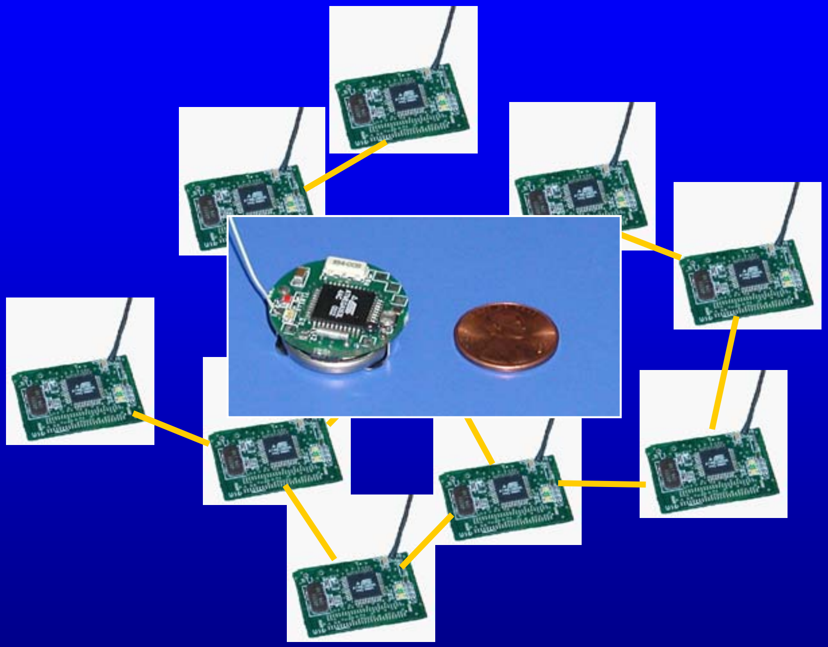


Configurable
Silicon Radio

MOTE
(a small piece of silicon)

Sensing +
Computing +
Storage +
Communicating

Networking 8.5B Computers / Year



Multi-Hop Sensor Networks

- Make it Personal
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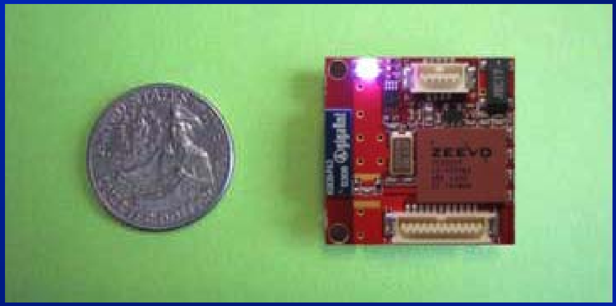
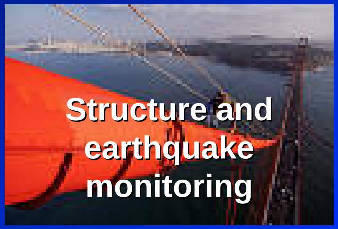
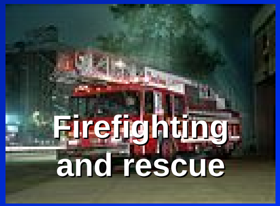
Deep Networking

Locally networking billions of embedded nodes; driving computing deeper into the infrastructure that surrounds us



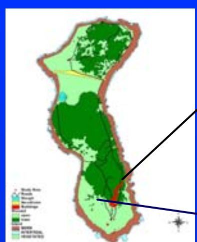
Applications





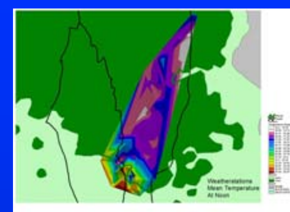
Sensor Network Application: Habitat Monitoring

From Macro-to-Micro: Surface and Burrow Microclimates



Study site highlighted

Noontime Burrow Temps (cool and uniform)



Noontime Surface Temps (warmer and variable)

GIS data visualizations courtesy of J. Anderson / COA

Occupancy Detection

Great Duck Island (GDI) Project Team

Alan Mainwaring, Intel | Robert Szewczyk, UC Berkeley | Joe Polastre, UC Berkeley | John Anderson, College of the Atlantic

Live Databases

- Make it Personal
- Closing the Loop
- Anticipation
- Dealing with Uncertainty
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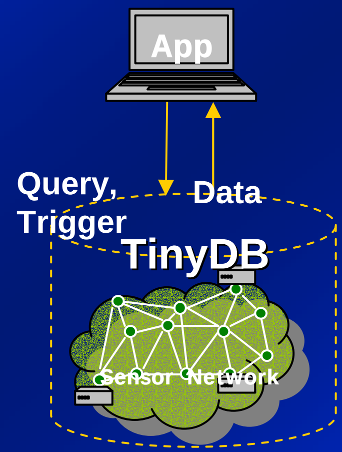
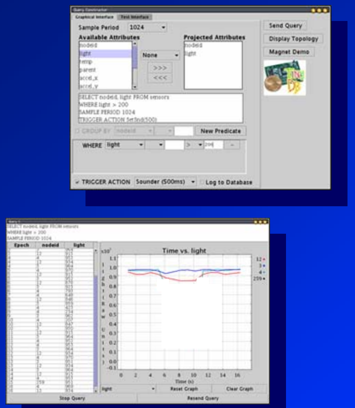
Planetary Scale Systems

Developing software that works across a wide range of diverse platforms & networks

- **DB-style queries over sensor network**
- **App simply issues queries & triggers to the network**
- **In-network query processing saves power, bandwidth**





http://berkeley.intel-research.net/tinydb/

Enabling the Real-Time Enterprise

- Make it Personal
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Planetary Scale Systems

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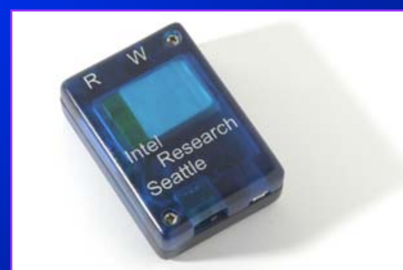
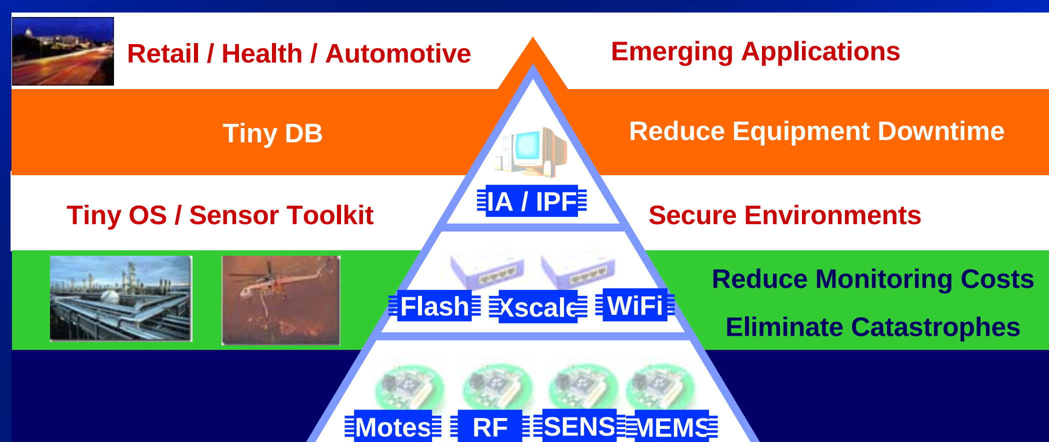


RFID Readers



Proactive Computing

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Tomorrow: Computers will be Proactive

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Machine Learning

- Make it Personal
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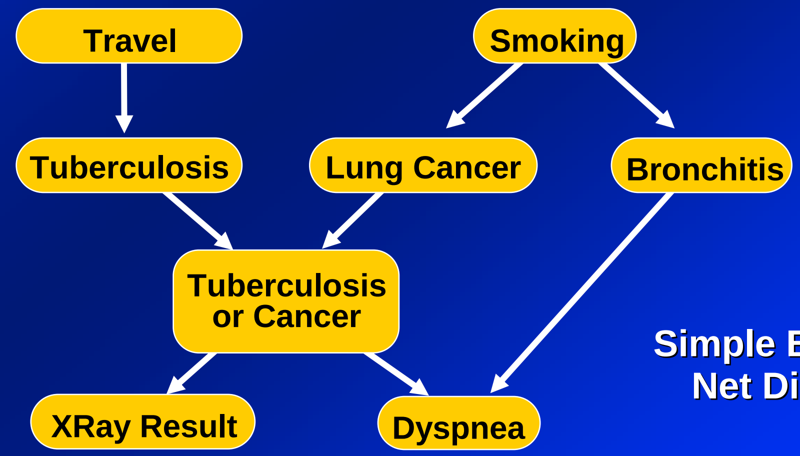
Dealing with Uncertainty

Using statistical modeling to deal with uncertainty inherent in the physical world

Deterministic → Stochastic

- **Hypothesize cause and effect relationships from raw data**



Simple Bayesian Net Diagram

Activity Inferencing

- Make it Personal
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Anticipation

Creating proactive software that anticipates our needs and produces answers before they are required

- ADLs include: brushing teeth, making meals, dressing, caring for infants – 23 classes in all
- Approach:
  - Put passive RFID tags on objects in the house
  - Sense when they are touched
  - Use Bayesian inference engine to deduce activities
- Experiment: 108 tags in a real house; 14 people

Recall/Precision

Activity	Prior Work	PROACT
Personal Appearance		● 92/92
Oral Hygiene		● 70/78
Toileting	○	● 73/73
Washing up	● 95/84	● 100/33
Appliance Use		● 100/75
Use of Heating	○	● 84/78
Care of clothes and linen		● 100/73
Making a snack	○○○	● 100/78
Making a drink	○	● 75/60
Use of phone		● 64/64
Leisure Activity		● 100/79
Infant Care		● 100/58
Medication Taking	○	● 100/93
Housework		● 100/82

Taking Action on our Behalf

- Make it Personal
- Closing the Loop
- Anticipation
- Dealing with Uncertainty
- Planetary Scale Systems
- Deep Networking
- Getting Physical

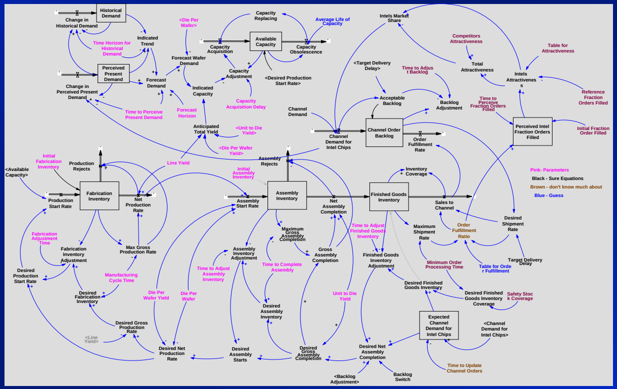
Closing the Loop

Bridging the gap between anticipating and acting on needs – predictably, and under human supervision

How many agents could you have?

- What is the limiting resource?
- If they "close the loop" autonomously, then how do we engineer the control systems that dampen their behavior?

Intel Supply Chain Modeling



- Simulation engine
- Analytical approach
- Working with real world data

Proactive Health

- Make it Personal
- Closing the Loop
- Anticipation
- Dealing with Uncertainty
- Planetary Scale Systems
- Deep Networking
- Getting Physical

Make it Personal

Empowering individuals and addressing their concerns over security and privacy

- **Goal: Empower individuals to assume responsibility for their own health**
- **Current Focus: Identify opportunities for technologies to enhance quality of life for Alzheimer's households**

"Stan"
severe decline
ensuring safety

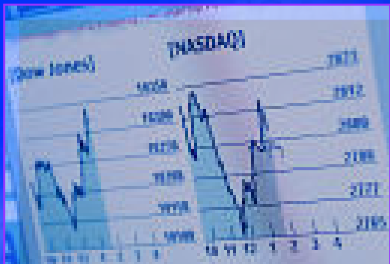
"Betty"
moderate decline
help w/ sequences

"Ben"
mild decline
rehearsing names

Center for Aging Services Technologies CAST

AAHSA American Association of Homes and Services for the Aging

Proactive Computing



Financial

Government

Health /
Life Sciences /
Agriculture

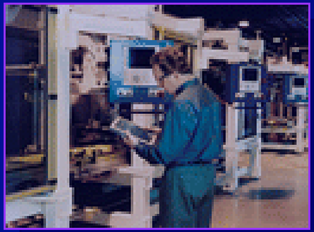
Environmental

IT

Transportation

Retail

Distribution



Manufacturing

Enabling Transition

We are on the verge of:

- a vast increase
- in the spatial & temporal fidelity at which
- we instrument & analyze the physical world.

This will enable real-time proactive computing

- It is starting to happen now
- Nanotechnology will accelerate the process

To probe further

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